TRANSPORTATION OF LIQUEFIED NATURAL GAS

This case describes the pioneer project in tanker transportation of natural gas

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PROJECT SIZE AND SIGNIFICANCE

In 1950 there was in Chicago and in other northern areas an unsatisfied demand for natural gas, which led to a one or two year waiting list of potential users wanting to connect to the gas line. At the same time, there was in the Texas and Louisiana area a supply of gas large enough so that many gas wells were capped and left unused. The building of a single gas transmission line was a two hundred million dollar capital expenditure whose justification required, by government regulation, a twenty year supply of gas in the ground near enough to the inlet end of the gas supply line to permit it to be economically collected at one point. At the receiving end of the line, the distribution piping was available, but in most areas the change-over from 500 btu gas to 1000 btu natural gas was a significant consideration.

The project on which this case is based was the liquefaction of natural gas by cooling it to minus 258°F at atmospheric pressure and shipping it as a liquid. This program involved the expenditure of about 24 million dollars over a period of eleven years before it became commercial. The first commercial step involved the expenditure of 180 million dollars and supplied about 8% of Great Britain's gas requirements at that time. The growth of the project has been such that it has been estimated that in 1971, less than ten years after its first commercial use, the world-wide expenditures for capital equipment for the transportation and use of liquefied natural gas amounted to three and a half billion dollars.

Risk capital for this venture came from an individual fortune controlled by a man who had the vision and the necessary willingness to take risks. Judging from the reluctance of the large oil companies to join in the venture when offered the opportunity, it seems apparent that they felt that their obligations to their stockholders did not permit them to take the risk involved.

The individual fortune involved was that of Frederick Prince Sr., who developed the Union Stock Yards in Chicago, and some of the railroads supplying it. The Stock Yards Amphitheater, the Stock Yards Bank, the Stock Yards Inn, a newspaper, the Union Stock Yards and Transit Company and large holdings in Armour and Company were all part of his interest. His successor, William Wood-Prince was always close to the transportation business and when the People's Light and Coke Company, in 1950, attempted to increase the industrial price of gas, he sought another source of gas for the Produce Terminal

generating plant which was the second largest user in Chicago. Because of his interest in transportation he knew that water transportation was the cheapest form and he also knew that gas could be liquefied. With this in mind he inaugurated the project of liquefying gas and barging it up the Mississippi River from the Gulf of Mexico to Chicago.

At the five million dollar point in expenditures, the Continental Oil Company was brought in as a partner, both to share expenses and to provide additional "know-how." At the 24 million dollar point, the Royal Dutch Shell Company became an additional partner for the next step of providing a commercial quantity of gas to England.

State of the Art

Natural gas is largely methane, which is the lightest hydrocarbon. Its thermodynamic properties are such that it is not practical to liquefy it by pressure as can be done with the liquefied petroleum gases (LPG) which are heavier hydrocarbons. Liquefied natural gas (LNG) can be liquefied economically only by cooling to minus 258 degrees Fahrenheit at atmospheric pressure. The change in volume is so great that a 50 foot high tank of liquid would have to be increased in height to five miles high in order to contain the same gas at atmospheric pressure without liquefaction. While liquefaction and storage of natural gas was not new, it had been used on a large scale only once before, in Cleveland, where a liquefaction plant and three large storage tanks had been installed fourteen years earlier. However, one of these tanks had failed unexpectedly, and as there were no containment dikes around the tanks, the resulting fire and disaster had cost over a hundred lives and millions of dollars in damage. The fact that this tank failure was unexplained had discouraged any other installations subsequently, in spite of the fact that one of the tanks had not failed even though it has been at the center of the fire. One suggested cause of the failure, which was an unexplained and sudden violent boiling of the mixture under certain laboratory conditions, had to be conclusively proven as not being a cause before confidence could be restored and another large scale venture undertaken.

General Economic Considerations

This project was unique as it involved use of an excess source of supply in capped gas wells throughout the world at the same time that an unsatisfied demand existed in consumer areas.

Thus it involved no problems in raw materials or in selling of the product. However, for this very reason it required a long range market evaluation of ultimate gas price.

The prototype liquefaction cycle was based on existing well head gas costs of about 6 to 8 cents per thousand cubic feet. Evaluation by our group at that time of the true value which gas would reach as a premium fuel compared with oil and coal led to a 60 to 90 cents figure. The actual price of gas in England at the start of the project was 100 to 120 cents. The present well head price of gas in interstate use in this country is government controlled at about 20 cents. The price for gas used within its own state lines and therefore not federally controlled is now almost twice as high as this government controlled interstate price. The price of LNG now being brought to this country and to England by tanker is about 90 cents. These widely divergent gas values and the initial underevaluation of gas produced in this country were all factors which had to be carefully considered.

The second liquefaction plant design used a more complicated cascade refrigeration cycle which consumed much less gas for liquefaction than did the prototype cycle.

The gas used for liquefaction with either cycle is only a fraction of the 20% of inlet gas used to pump gas through typical pipelines from Texas to New England.

Personnel Involved

As mentioned above, Mr. William Wood-Prince made the project possible by supplying financial support. He enlisted the support of Mr. Willard Morrison who had done work during the war on freeze-drying of plasma and who developed the Deep-freeze operation and coined the word Deepfreeze which was the beginning of relatively large scale household use of frozen foods. Mr. Morrison brought in Mr. Edwin Brown, retired Vice-President of engineering at Allis-Chalmers, and Mr. Harold Hagan, a well-known authority on blowers and compressors. My position was generally in charge of the tank design and insulation and in joint charge of the prototype tests.

At the peak of the project, about 80 men were on the payroll, most of them at the shipyard where the cargo barge and the liquefaction barge were being built.

Basic Technical Problems

1. How to explain the sudden violent boiling under certain laboratory conditions.

2. Iron and steel become brittle at the low temperatures necessary and will fracture in a manner similar to glass. The tanks in Cleveland used a nickel steel alloy with about 8% nickel to avoid this embrittlement, but the supply of nickel for a large scale use and the high cost required study.

3. Tank Insulation. Even though the tank could be built of nickel alloy, the hull of the ship would become prohibitively expensive if made of this same material. It was therefore necessary to find an insulation for the tank which would serve as a second line of defense and prevent the liquid from reaching the ship's hull in case of failure of the inner tank. Most insulation materials were porous and could not be used. Foam glass and foam plastic insulations with closed cells were possibilities, but they became brittle so that the shrinkage at low temperatures would open cracks and make them unsuitable. Some materials, such as balsa wood, would not become brittle, but their shrinkage was such that they required pre-compression in order to reach the low temperatures without cracking.

4. Tank size, shape, and insulation thickness and the need for on board refrigeration equipment required study.

5. Thermal K-factor tests were needed to accurately compare insulation materials for low temperature use, as adequate manufacturers' data were generally not available at these temperatures.

6. The tank insulation and construction decided upon was new and unique and new methods of fabrication had to be devised.

7. Testing location and hazards required consideration.

8. Liquid methane disposal and associated fire hazards required demonstration.

9. Meeting Coast Guard requirements was mandatory.

10. Thermal stresses were important because the liquid being stored was cold, the vapor above it would stratify, and this stratification would produce severe thermal stresses in any metal tank walls. A fifty foot diameter metal inner tank such as that studied for ocean transportation would shrink in

diameter by about two or three inches at LNG temperatures. Thus the tank would have to be essentially self-supporting and means of anchoring both at the top and bottom would have to allow for this shrinkage.

11. The original liquefaction plant was designed to use well head pressure of 1000 psi for the first stage of the refrigeration cycle. Thus a decision was needed as to whether the liquefaction plant should be built on a barge so that it could be moved or should be built on a permanent foundation. Initial well head pressure of a typical new well was more than adequate, but this pressure decreased during the life of the well.

12. In an oil tanker, the oil is normally carried directly against the hull and the ships ribs and keel and braces are surrounded by the liquid. In the case of a methane tanker, the ship would have to be double-hulled as it is essentially impossible to insulate a metal rib which is exposed to cold on both sides.

DISCUSSION OF BASIC TECHNICAL PROBLEMS AND DESIGN

1. Violent boiling. This was a very infrequent laboratory observation which was not considered significant until it was advanced as a possible cause of the Cleveland disaster. The first step was to continue to extend laboratory work in handling LNG until the phenomenon was encountered and then to duplicate and examine the conditions which caused it. Minor instabilities were known and the eventual answer was found by repeatedly promoting these and analyzing them and showing that the instability could be increased to the point where it would explain the "explosive boiling" previously encountered and subsequently advanced as a possible cause of the Cleveland disaster.

The known instabilities occurred when LNG contained in a dewar flask had fractionated by slow boiling until the heavier hydrocarbons became concentrated. If this was done with LNG having an initial higher percentage of heavies (well head gases vary from 60 to 90% methane and the pipeline gas available in the laboratory had about 92% methane) and if it were done in the best available tall dewar flask which was completely isolated from mechanical motion and shock subsequent to filling, then the heavier hydrocarbons would settle to the bottom and warm up (without boiling) to a temperature above the boiling point of the lighter methane in the top layers of

the remaining liquid. After this condition was reached, any small particle dropped into the flask or any motion changing the gravity induced density separation and resultant temperature differences would produce a cumulative boiling and mixing during which the methane components would boil violently because of being mixed with higher temperature components previously isolated in the bottom of the flask.

One of the dewar flasks used had a 1/4 inch wide band on each side from which the normal mirror-like reflective coating had been omitted so that the contents could be observed from the side as well as from the top. The sudden violent boiling phenomenon could not be produced in this flask because the clear spaces caused continuous local boiling whose mechanical motions were adequate to prevent the necessary stratification. Whether the phenomenon being investigated was 100% due to stratification or was partly due to superheating of the methane above its boiling point could not be determined, but the result would have been the same in either case.

2. <u>Embrittlement of steel at low temperatures.</u> Ferrous metals are normally ductile and any overstressing will cause a ductile distortion prior to failure. The fact that ductile steel when cooled could at times fail in a brittle fashion like glass was known. However, putting accurate numbers on embrittlement was impossible because it varies greatly with thickness, rolling procedure, residual gas content, alloy content, and other similar variables even in completely annealed samples. Its onset temperature was as high as 30°F in some specimens and was below minus 320°F in others. This embrittlement phenomenon was under study at the time because it had been advanced as a cause of failure of large turbine rotors when the inlet cooling air had been allowed to drop to outdoor winter temperatures. Because of embrittlement possibilities, use of a steel tank was not possible.

The first alternate to steel was a nickel steel containing at least 8% nickel. Such a material had been used in some of the Cleveland tanks referred to on Page 2. However, (1) these tanks had failed, (2) the cost was high, (3) the world supply of nickel was not adequate for the ultimate fleet of tankers that was probable, and (4) a tanker hull which would resist embrittlement in case of tank failure was considered necessary by the Coast Guard, where approval of vessel design was essential.

The second alternate was aluminum, which was also expensive and which also could not be used in the hull.

The final material selection for the tank lining was not made until the question of tank insulation was answered. The development of an insulation (as described later) which would protect the hull in case of tank lining failure made the use of an "inside insulated" steel tank possible for the first project which involved only river and canal shipment. The second project which shipped gas to England used heavy aluminum tanks inside a similar hull protecting insulation, and some later designs used a metal "membrane lined" tank.

3. Tank Insulation. The "inside insulated" tank which was developed to meet the above requirements was actually a balsa wood tank of very special construction inside a steel tank. Wood tanks for oil storage had a long and successful history although they had been superseded by steel tanks but their low temperature characteristics were favorable and justified their reconsideration.

All non-porous (closed cell) plastic and ceramic insulation materials available at the time were tested to see if they could be cooled to minus 258°F without cracking when they were attached to (or held by liquid pressure against) the inside of a steel tank which remained at ambient temperature.

None would pass this test. In other words their thermal contraction for this temperature change produced tension stress which exceeded the ultimate strength of the material. Furthermore materials which were not brittle at room temperature tended to become brittle at the low temperatures needed. Natural materials, such as wood, however, did not become brittle even though they would shrink and crack.

The material finally selected was low density (about 4 to 7 lb. per cu. ft.) balsa which was precompressed so that thermal shrinkage had to relieve precompression before it would start to produce tension (the cause of cracking). This use of elastic pre-compression to prevent cracking is similar to the "tempering" of glass to put its surface layers in compression thereby decreasing the onset of tension in the surface layers, which tension would open small latent cracks in the surface and initiate characteristic brittle material failure.

While balsa wood is quite porous in the grain direction (sap flow direction), it is relatively "closed cell" in the other two directions. However, the need for a closed cell was only partial, because a liquid at its boiling point could not penetrate the insulation without becoming a vapor which would force the liquid back out of the insulation. The actual

requirement was for a material impervious enough to prevent upward escape of the gas great enough to relieve or reduce back pressure of the gas on the liquid. The principle is illustrated by the tank construction of Exhibit 1 in which thin metal walls contain the gas which is actually an excellent non-conductor of heat. The thin walls are close enough together to minimize convection, and are thin and extended in length to reduce heat losses through the metal itself. Such a metal and gas tank insulation is basically sound for a stationary tank, but becomes complicated and was judged impractical for a large shipboard tank.

4. Tank Design. Numerous small tanks were built using different insulating materials and using different amounts of precompression. The largest of these tanks was ten feet in diameter with twelve inches of compressed balsa insulation applied in the same manner that was expected to be used in the final tanks. This tank was kept filled with liquid nitrogen continually for over a year and at one stage was put on a truck and transported for quite a few hundred miles to show that the motions of a tank at sea would not change the characteristics. The basic principle of holding a boiling liquid in a metal tank with internal semi-porous insulation was demonstrated by drilling holes from the outside of the tank through the insulation and into the liquid. If these holes were slanted with the lower end being at the liquid end, then the gas which built up due to the boiling of the liquid would keep the liquid from entering the hole if the outer end of the hole was properly corked. If the hole slanted upwards so that the upward end of the hole was at the liquid end, then a cold spot would be generated on the metal of the outer tank. This was done to simulate defective insulation and to test a proposed method of dealing with such a defect if it became necessary. The method of correcting such a leak was to inject a hot wax into the outer end of the hole. If injected rapidly enough, this hot wax would penetrate a significant distance before it congealed and would substantially correct the cold spot on the outside of the tank.

The barge which was built had five cylindrical tanks, each 50 ft. in diameter and 25 ft. high. See Exhibits 2 and 9. It was volumetrically the largest barge ever built for inland waterways. For prototype tests only two tanks were insulated. This was to reduce the expense and risk and also was because it was apparent by this time that the most economic initial commercial use was across oceans where there was no pipeline competition, rather than up the Mississippi River where pipelines were competitive and were shorter in length.

To further reduce time and expense and to provide more severe testing of the balsa wood insulation, one of the two tanks had a wall thickness of only four inches instead of the design thickness of twelve inches which was used in the other tank.

No refrigeration equipment was necessary in tanks as large as these, because the boil off rate with good insulation was only a fraction of a per cent a day, and the ultimate intention was to use boil off gas as fuel for ship or tug propulsion. In fact the boil off rate was only three or four times the boil off rate of 100 octane aviation gas in normal tankers. Exhibit 3 is a photograph of the visible boiling around the edges of the tank. No bubble type boiling was visible except around the edges of the liquid surface.

Because the question of sudden violent boiling had been raised as a possible cause of the Cleveland disaster, provision for this possibility was made by use of a 5 foot diameter relief valve in each tank. It was necessary to do this to answer all questions of the Coast Guard and other safety concerned interests. The valve was incorporated in the top insulated wall of the tank and consisted of a hinged metal plate insulated with 12 (or 4 in the second tank) inches of balsa with a stepped taper joint around the balsa periphery.

5. Thermal insulation tests. Thermal conductivity of various insulative materials is found in handbooks and can be obtained from the manufacturers. Frequently however, this information is not tied in with a specific temperature at which the tests were made and also it has been found that the tests themselves are inherently subject to misinterpretation and some of the figures available were not reliable. Steady state tests of thermal insulation were attempted but the required precision was found difficult to obtain because of the difficulties of shielding and of maintaining stable thermal inputs and outputs. Also the necessity of having thermal insulation figures which were applicable at very low temperatures made the standard methods of thermal insulation testing exceedingly difficult. For this reason a very simple test was designed which could be used with all types of insulation in the same set-up and which could be run very rapidly. While these tests were not particularly precise in giving thermal conductivities at a given temperature, they were nevertheless far more precise when it came to comparing different insulation materials and when it came to evaluating them under the conditions which would be encountered.

The thermal insulation test which was devised consisted of placing about two inches of insulation around a one foot square by one inch thick piece of aluminum and enclosing the entire insulated metal in a cardboard carton. By chilling the piece of aluminum to liquid air temperatures of minus 320°F and by quickly placing it in the insulated box, it was possible by recording the temperature of a thermocouple on the block of aluminum to obtain a time/temperature curve which was an adequate measure of the thermal conductivity of the insulation being tested. This test was run not only on the insulations which were candidates for the final tank but also on numerous other standard insulating materials for which comparisons were of interest. A chart showing the comparative thermal conductivities of numerous insulating materials as determined by these tests is shown in Exhibit 4. One of the fundamental facts demonstrated by these tests was that insulation materials in which the enclosed gases are of the halogen family are of considerably lower thermal conductivity than those in which the interstices are filled with air. This was the expected result because it is known that the halogens have a lower thermal conductivity than does air. However, the halogens become liquid at temperatures of minus 50 to plus 20 degrees and the effect of this fact was not known. Also it was found that the insulation materials which have halogen gases in their interstices lose their thermal insulating characteristics slowly over a period of years due to diffusion of the halogens outward through the partly permeable cell walls and diffusion of air inward through these same walls.

Another interesting test made with this equipment was the use of aluminum barrier type insulations with the intervening spaces filled with air. It was found by these tests that when the spacing approached a quarter of an inch the thermal conductivity approached that of air by itself and was about as good as the best insulating materials. Points shown on the attached chart cover several spacings of such aluminum barriers. See Exhibit 4. These tests were valuable comparisons even though they did not distinguish between convection between vertical walls, convection between horizontal walls or stratification between horizontal walls.

6. <u>Tank Insulation and Construction.</u>

a. Balsa procurement: The availability of an adequate supply of balsa of proper density was a major consideration as was the size and shape of the pieces of balsa obtainable from the relatively small, fast growing, scattered tropical tree which became denser with age and in which only about

1/4 to 1/3 of the trunk was of proper density under the best of conditions. The entire balsa lumber industry was inherently small, and mostly used for toys and models at the time except that during the war a crash program had taken place for the balsa core of the very successful plywood "Mosquito" fighter plane England built in great numbers in the absence of adequate aluminum supplies. Although the balsa supply was concentrated in Ecuador and relied on natural and not farm trees, the fact that typical age of desirable trees was only five years made long range uses and expansion of supply feasible.

The small size of the tree yielded only small lumber, typically 4 x 6 x 60 inches for a large piece, and lumber which was of several thicknesses from 1 to 4 inches. See Exhibit 5. This limitation was overcome (although at the expense of a high scrap ratio) by using a large high frequency electronic glue drying machine to fabricate 4 ft. by 16 ft. panels, which were then used as the basic building blocks.

b. Moisture and humidity control. Wood is highly hygroscopic and it dimensions change with moisture content. The balsa used was no exception. It had been kiln dried at the lumber yard in Ecuador, but after assembly into large panels, it was stored in a hot room until ready for final sizing and delivery to the tank whose atmosphere was not only temperature controlled, but also humidity controlled. Moisture absorption was so rapid that the time from final sizing to delivery to the tank was limited to small fractions of an hour. The moisture content when installed was about 7%.

c. Gluing procedure for balsa pre-compression. Two types of glue (adhesive) were used because wood-to-wood and wood-to-metal adhesion are different. A wide variety of glues was tested at all temperatures, and the final solution was to spray the entire inside of the metal tank with a vinyl base type of glue to which the cascophen type wood-to-wood glue would adhere.

Pre-compression of the balsa during gluing required considerable experimentation to develop production tools and methods. The 4 x 16 foot panels required about 1/4 inch compression in the lengthwise direction and 3/16 inch in the four foot dimension. The greater compression across the grain was due to greater contraction and greater flexibility in this direction.

The wood-to-wood glue was a two component cascophen type which had a short life (a fraction of an hour) after mixing even under optimum temperature conditions. The gluing procedure

adopted for the walls used a vacuum blanket to maintain contact pressure during drying. The pre-compression was obtained by using panels anchored to the wall by vacuum pads as movable back-up anvils from which pressure could be applied by air cylinders to shoes which pressed against the balsa panels. A pictorial sequence showing the steps in gluing one 4 x 16 ft. panel (made up of three 1/2 inch panels to more easily conform to tank curvature) is shown in Exhibits 6, 7, and 8 and explained in captions.

Even with the most carefully controlled steel tank fabrication, the variations from a true right cylinder shape were of the order of magnitude of an inch (only 1/6% of the 50 ft. diameter). To correct this irregularity so that hand fitting could be avoided, the first layer of balsa was planed (honed) to an accurate cylinder by use of an accurately machined central column with a rotating arm on which an electric planer was mounted.

7. Testing. One thousand pounds of well head gas pressure was required for the liquefaction plant (shown in Exhibit 9) so that testing with methane was done near a gas well. However, an initial trial run was made at the shipyard using liquid air. Two inches of liquid air was stored in one tank for a few days. It was liquefied with the same equipment and cycle designed for natural gas, and its lower temperature (-320°F instead of -258°F) subjected the tank to 20% above its design temperature range.

Tests with LNG (liquefied natural gas) at the well head covered a period of several months and curves of tank level vs. time are shown in Exhibits 10 and 11. The tanks were scavenged with inert gas both before and after filling. Out-gassing of the balsa after the test required about five days to meet normal Coast Guard safety limits.

8. Methane disposal and fire hazards. During the prototype tests, substantial quantities of liquefied natural gas would have to be disposed of as it could not economically be recovered on the erratic test basis required. This provided an opportunity to investigate personal and environmental hazards that would occur in actual operation in cases of accidental pipeline failures or in case of actual ship damage. One of the rigid Coast Guard requirements was that no gas could be used for ship propulsion machinery so that flaring of boil-off gas was necessary during normal operation as well as during testing.

The first step was investigation of the flaring of natural gas. Color pictures were taken, ignition distances were established, and fire damages distances established for flares up to a quarter million cubic feet per day. The next step was disposal of the liquid methane output of the liquefaction barge. This was a continuous process over a period of many days, and involved the burning on water of liquid methane which was the equivalent of three million cubic feet per day. The third step was investigation of the burning of the full output of the pumps which had been installed in the cargo barge for the unloading of the methane. This involved burning on water of twenty-five million cubic feet a day. Plotting of these tests gave a straight line curve on log-log paper, the slope of which was such that when the quantity of gas burning is multiplied by a thousand, the distance radiant heat is damaging is proportional to the cube root of the quantity of gas being flared. These tests covered three decades of flow rates, and by projecting this curve another two decades, it was possible to arrive at an estimate for the worst catastrophe envisioned, which was the collision of a ship. Under this condition, the distance the heat was damaging was only five hundred to a thousand feet, which is roughly one ship length. It appears therefore that liquid methane when discharged upon water under normal atmospheric conditions does not spread very far because when it becomes a thin film it is immediately evaporated by the much warmer water on which it rests, and being lighter than air after it warms up part way to atmospheric temperature, it immediately rises and creates a draft which prevents any of the gases from spreading significantly. Ignition conditions under normal atmospheric conditions did not appear to exceed about 25 feet, and ignition was accomplished without any evidence of explosive effects. These tests were vital parts of the project for the consideration of the Coast Guard and for the consideration of the safety aspects of any large financial investment.

ADDITIONAL CONSIDERATIONS

1. Coast Guard inspection of every vessel was mandatory and extensive regulations and design requirements were in existence. However the most pertinent tanker regulations were based on experience with 100 octane gasoline and LNG transportation had never been considered. Furthermore, there was no Coast Guard provision for experimental ship operation (although such an experimental category did exist in Great Britain). As new regulations required a lengthy procedure of promulgation, public hearings and approval, the procedure

adopted was to meet all existing regulations for similar materials even though some were not entirely pertinent. Many meetings were held and the Coast Guard inspector was kept fully informed and followed all phases of construction and testing. Their cooperation was troublesome at times but was adequate when the rigidity of their normal regulations and the extent of the new problems were considered.

2. Thermal stresses. This problem of thermal stress was not of concern in the prototype barges because they had internal insulation, but was of vital concern for the ocean going tankers which were being studied at the time. Actual test measurements of the thermal gradient in the prototype storage tanks did confirm that thermal stress was a major problem in the design of the metal tanks which were used on the sea going vessels which were the first commercial application of the process.

The design of storage tanks seldom involves any consideration of thermal stresses because the contents are at atmospheric temperature or above, and under these conditions thermal convection currents will exist which will reduce any sharp gradients. However, when a cold liquid is stored in a tank there will be no thermal convection currents, but instead there will be stratification. If the liquid is stored at its boiling point as is the case with the liquefied natural gas, then the boiling action will produce some gas movement, but the amount of this movement is difficult to calculate, and in the large well-insulated tanks contemplated, the estimated gas movement due to boiling would be very minor. Thus the problem of thermal gradients in a ship-mounted tank when the ship was in port and was absolutely stationary became a major problem in design. One of the interesting landmarks found in the literature to confirm this conclusion was a report of actual strain-gauge stress measurements on a typical oil tanker. Three conditions of significant stress were found. The first was the stress in the hull when the ship was supported at each end by wave action and was substantially unsupported at the center. The second stress, which was significantly higher, was that occuring in a ship in still water in which the two end tanks had been loaded and the center tanks were unloaded. The third and slightly higher stress was that occuring on a ship in which the bottom of the ship was at water temperature in cool water and the top of the ship was exposed to heating caused by direct action of the sun on the upper structure.

3. Other problems. Many other problems too numerous to discuss in detail were encountered and investigated in the course of the project. These included drilling a gas well which had to be in a location adjacent to a barge canal so that gas and well head pressure could be assured. Later cooperation with Continental Oil led to the use of one of their wells rather than the well which was drilled for the purpose. The cargo barge which was tested as a prototype was made the subject of tow-tank tests in order to arrive at the most desirable bow configuration and the most economical barge configuration. The tug was a separate vessel but was actually a pusher type tug which was originally attached to the rear of the barge because it gave a more controllable arrangement than did the towline pulling of a barge which had previously been used on the Mississippi River and which was extensively used on the Rhine River. The decision to mount the liquefaction equipment on a barge rather than on a permanent foundation was made because of well head pressure of 1000 psi as the first stage of the refrigeration cycle. This led to problems of balancing, clearances, alignment, which became major problems because the compressors consisted of two lines of about four compressor wheels each which were connected with flexible couplings to each other and to the two shafts of the step-up gear through which a standard 3600 rpm steam turbine drove the compressors at 12,000 rpm. In the final operation it was found, for example, that the vibration at the worst bearing would vary with the direction from which the sun shone upon the barge. During the course of the project, trips were made to Ecuador where the balsa lumber mills were inspected and where low-level flights over the jungle were made to inspect the supply of balsa trees which grew individually rather than in groups and were scattered throughout the forest. Trips were also made to Mexico City to discuss the supply of gas in the Isthmus of Tehuantepec and the prices at which it would be available. All of the oil and gas in Mexico was under government control.

4. Patents. It was known from the beginning that fundamental and complete patent protection could not be obtained and that there would be competition regardless of the number of patents obtained. The liquefaction of natural gas and its storage in large tanks had been accomplished at Cleveland some years before and the use of similar tanks on barges or ships would not be patentable. In spite of this, a strong patent program was undertaken to prevent any future competition from taking advantage of details and improvements which had been developed and paid for in the course of our pioneering work. These patents would take on value as protection for an integrated system which had been developed

and tested and would mean that competition would have to do their own developing testing of different ways of accomplishing the same results before they could hope to obtain financial support on a project which required one or two hundred million in investment. A summary of all the patents is not available, but my own contribution was twelve United States patents on various aspects of the tank design and the liquid storage. Most of these patents had equivalent coverage in five or six foreign countries as well.

5. New corporation. After the completion of the prototype tests, a new company called Constock Liquid Methane Corporation was set up to carry on the work under the joint ownership of Continental Oil and Chicago Stock Yards. Their first activity was the conversion of a C3 cargo ship into a small liquid methane carrier which operated between the Gulf of Mexico and England for a year. This ship also had balsa insulation but it had an aluminum tank inside of the balsa. The design of this aluminum tank was undertaken by the A. D. Little Co. and it was necessary to convey to them the importance of thermal stresses and for them to re-design their tank on the basis of this experience. The importance of this subject was unfortunately very forcefully illustrated about this time when one of their engineers lost his life due to the sudden rupture of an experimental tank of cold liquid.

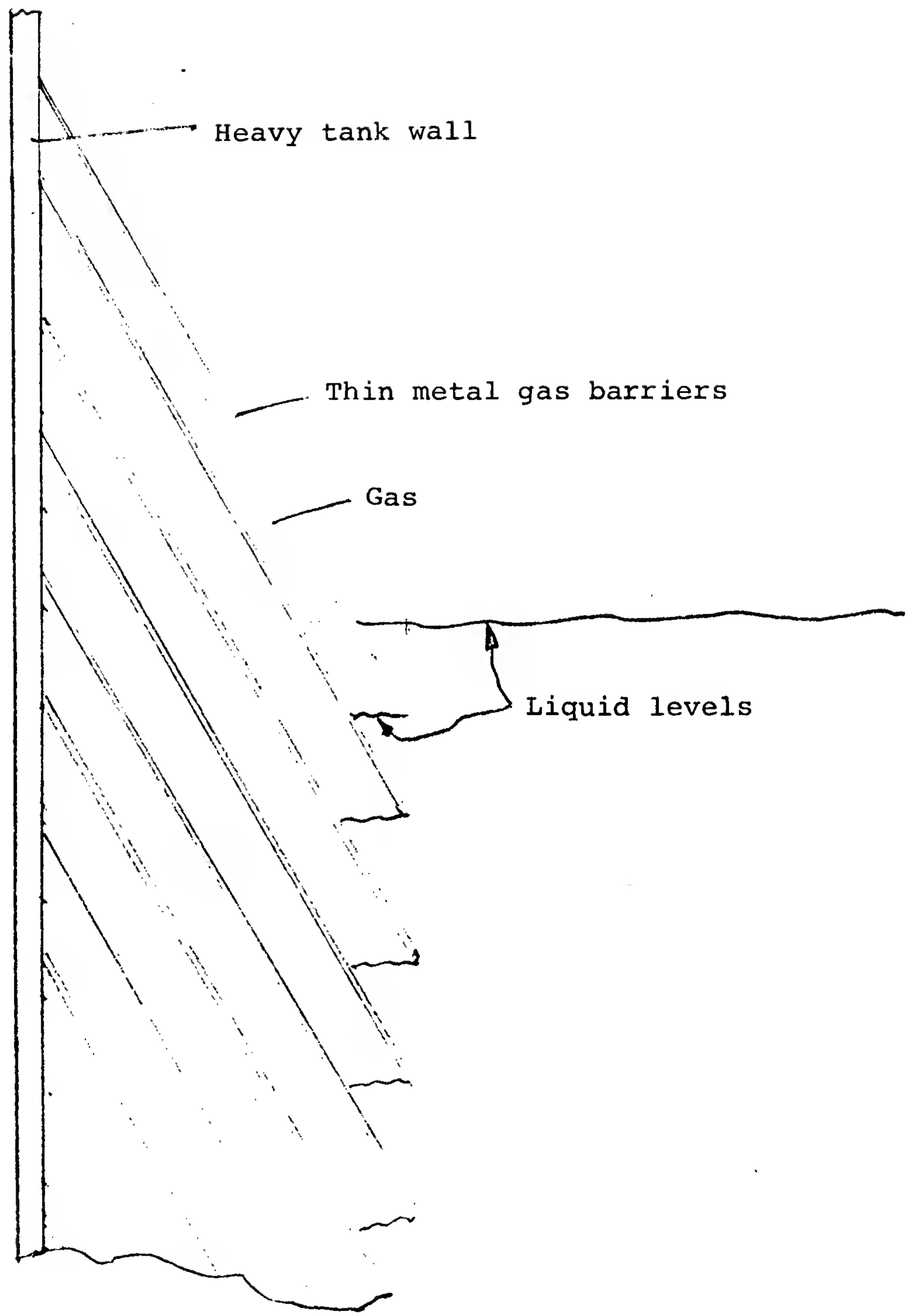


EXHIBIT 1

Metal tank insulation
suitable for boiling liquids

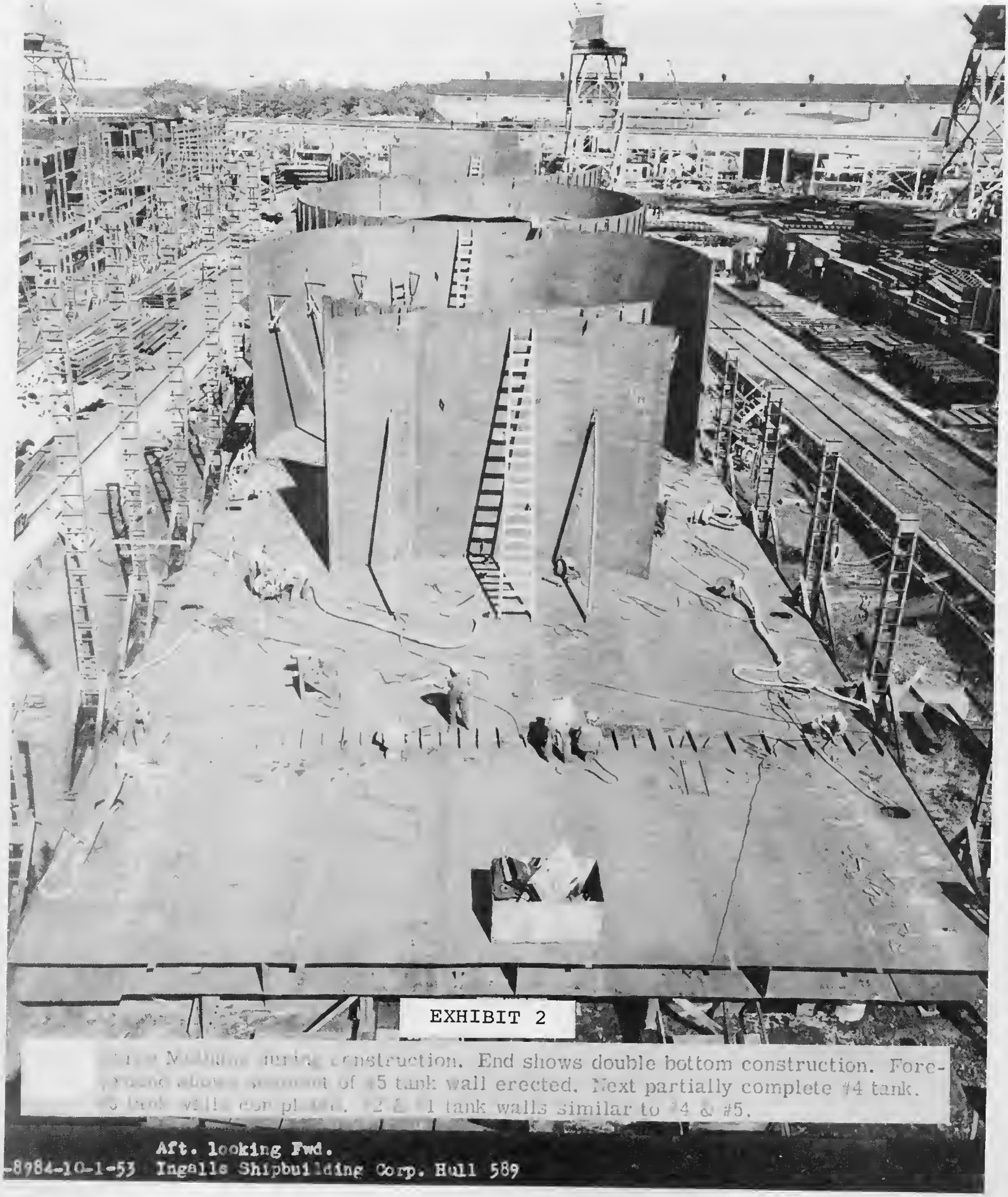


EXHIBIT 2

[illegible] during construction. End shows double bottom construction. Foreground shows segment of #5 tank wall erected. Next partially complete #4 tank. #3 tank walls completed. #2 & #1 tank walls similar to #4 & #5.

Aft. looking Fwd.
-8984-10-1-53 Ingalls Shipbuilding Corp. Hull 589

EXHIBIT 3

Visible boiling around
edges of tank

ECL 198

SB57-0803-

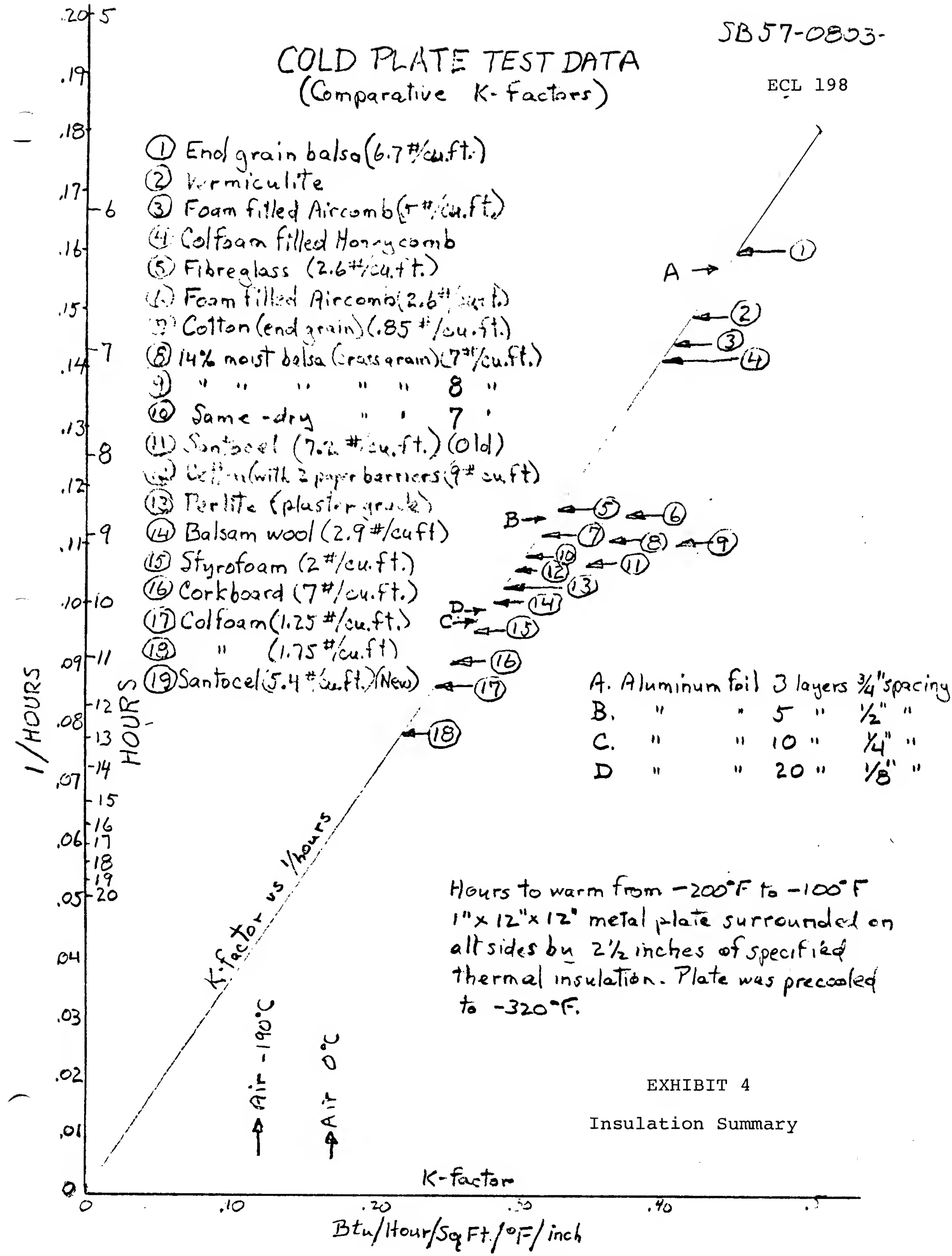


EXHIBIT 4

Insulation Summary

EXHIBIT 5

Balsa (as received)

EXHIBIT 6

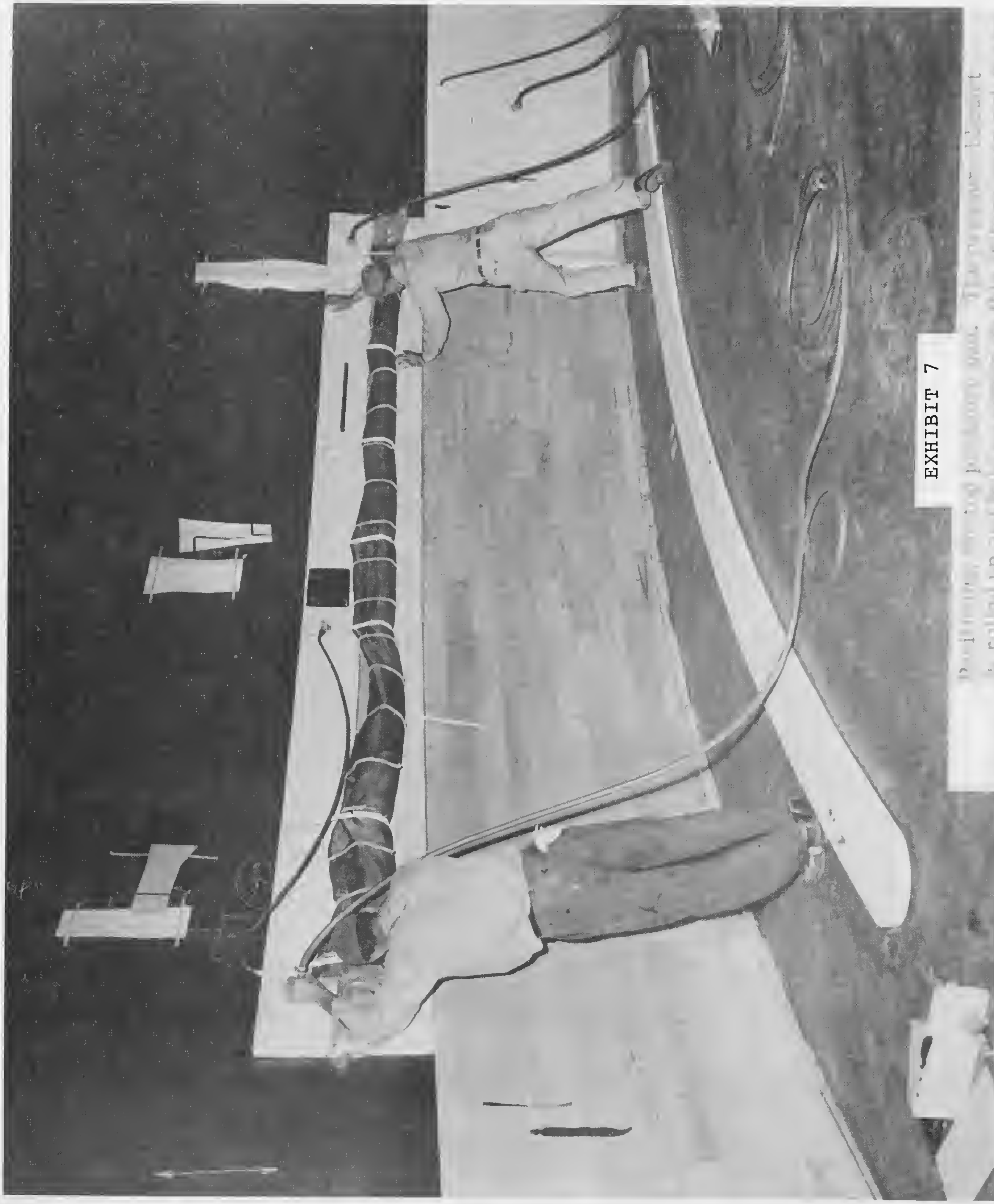


EXHIBIT 7

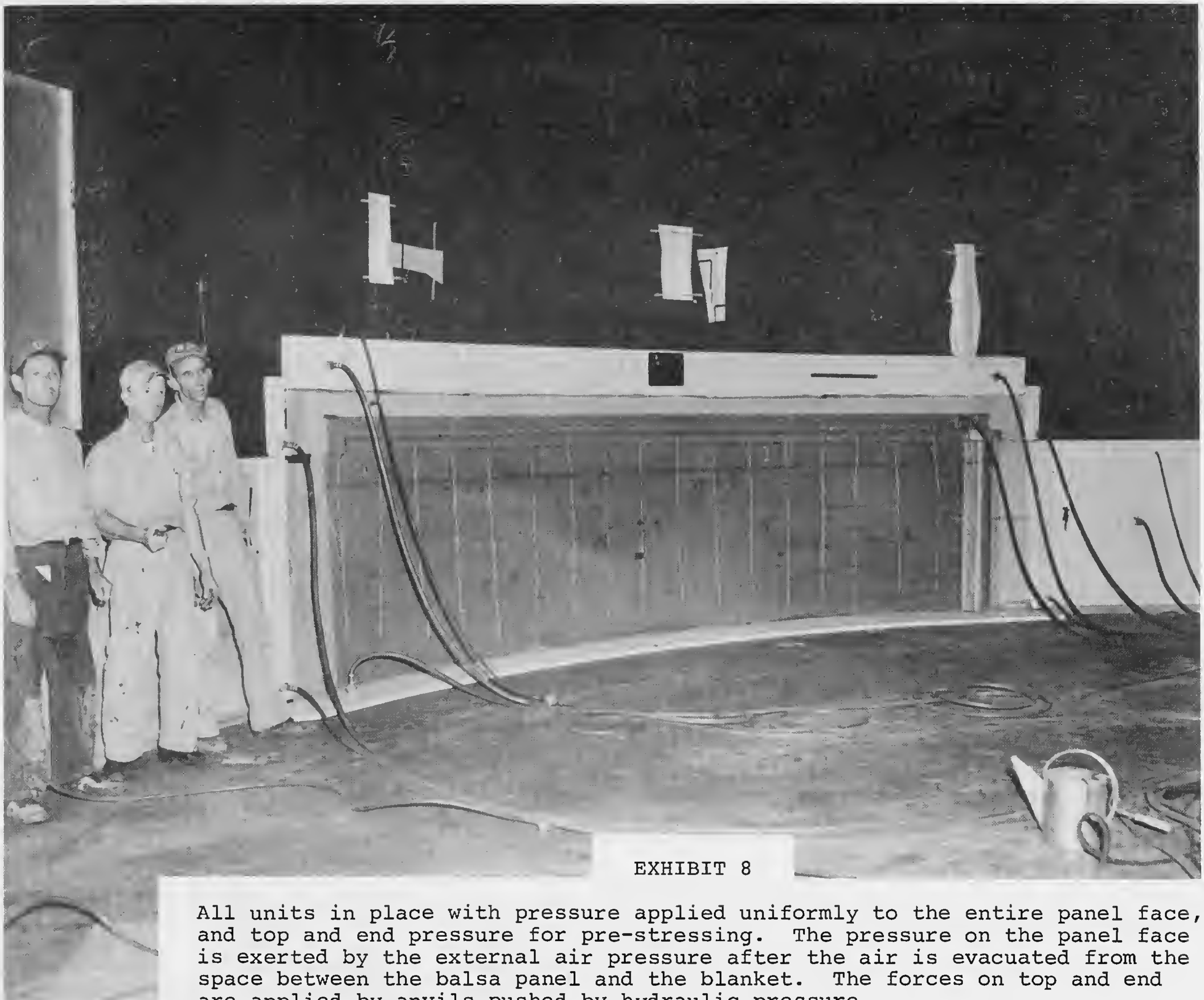


EXHIBIT 8

All units in place with pressure applied uniformly to the entire panel face, and top and end pressure for pre-stressing. The pressure on the panel face is exerted by the external air pressure after the air is evacuated from the space between the balsa panel and the blanket. The forces on top and end are applied by anvils pushed by hydraulic pressure.

EXHIBIT 9

Bayou Long Test Site
Liquefaction Barge in Center
Cargo Barge at Left
Quarter Boat at Right

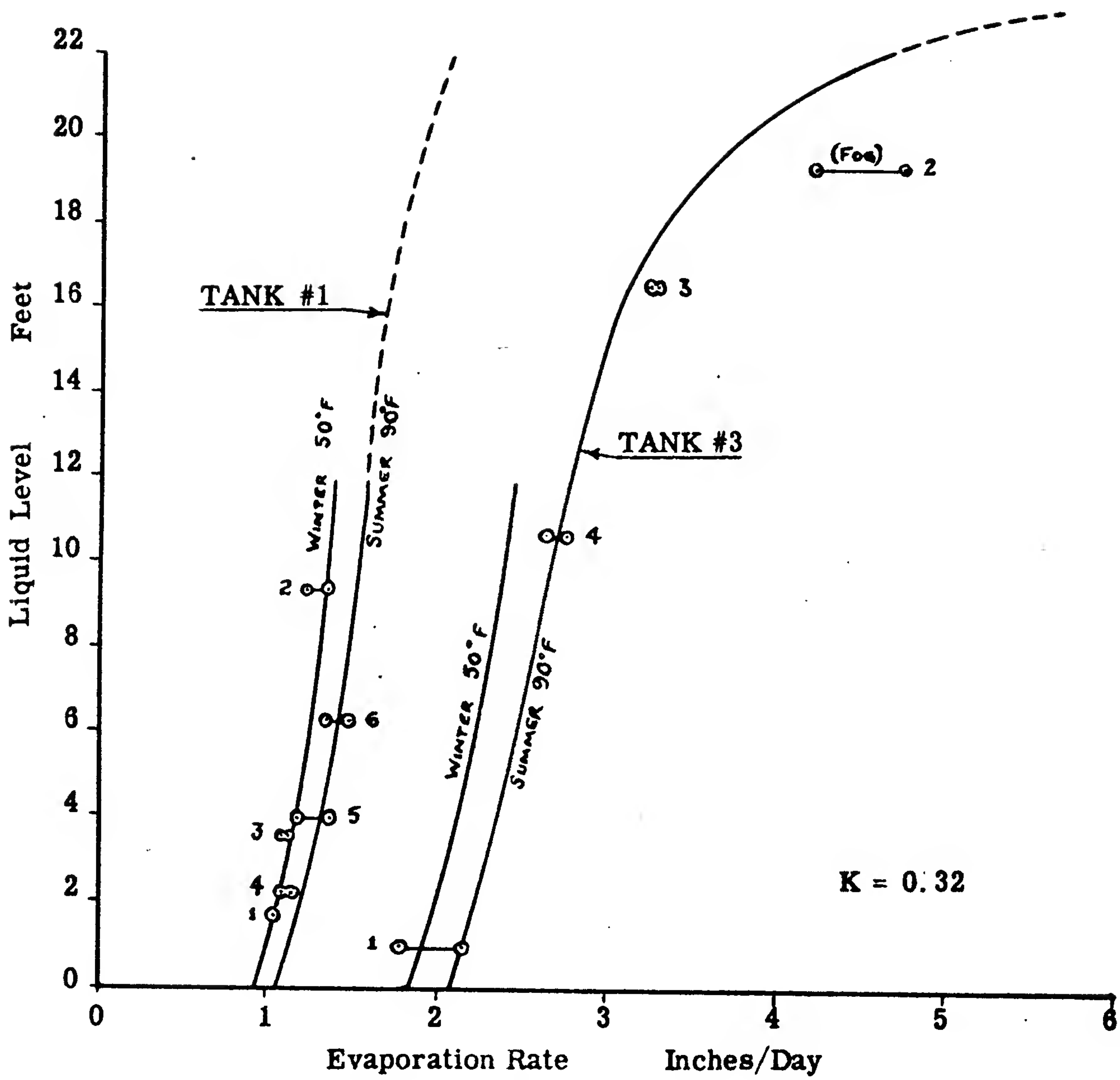
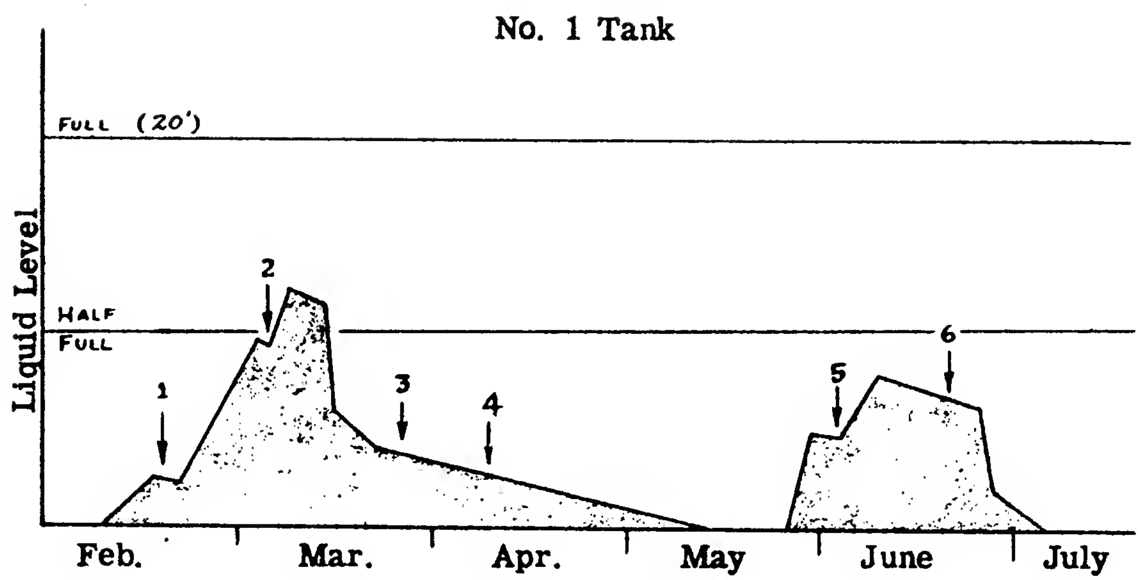


EXHIBIT 10

EVAPORATION RATE FROM CARGO BARGE



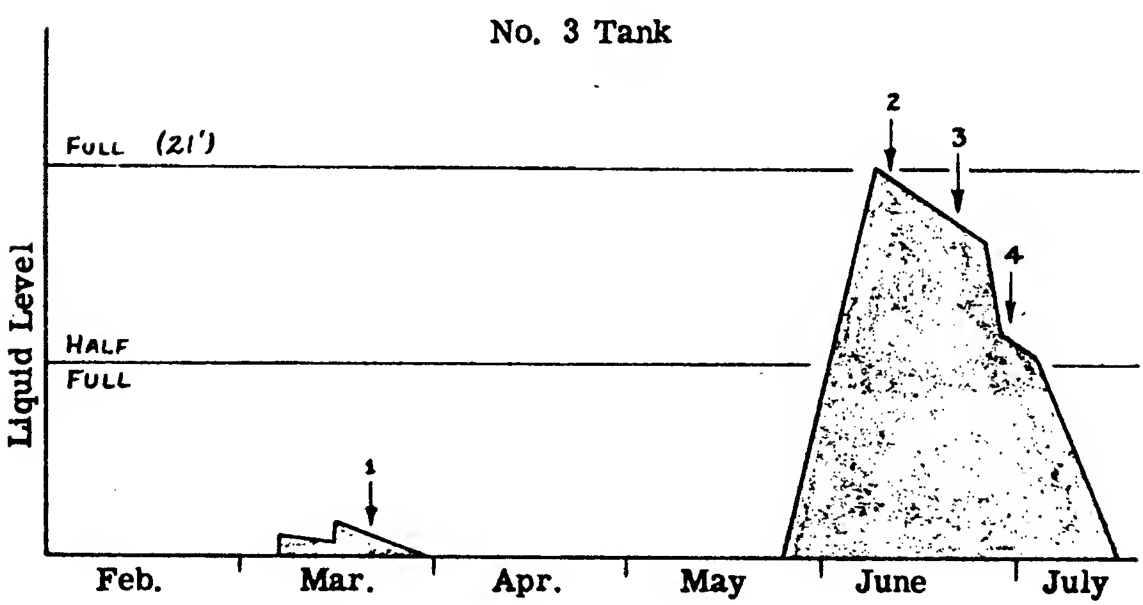


EXHIBIT 11

TOTAL TEST TIME vs. METHANE LEVEL

TEACHER'S NOTE

This case is suitable for beginners as background for exercises in approximate estimations, for more advanced students as practice in working with engineering problems far removed from the usual curriculum content. Interactions between economic factors, engineering developments, and the ability to take risks are the subjects of another series of suggested questions.

I. Some suggested exercises in approximate estimations:

1. How much does a steel tank 50 ft. in diameter and 25 feet high weigh empty, if it is made of 3/4 inch thick steel and lined with 8 inches of balsa wood? How much does it weigh full if liquid methane weighs 50#/cu.ft. ? How accurate do you expect these calculated weights to be?

2. How much lower than the empty ship will the full ship float in the water? The size and shape of the ship can be estimated from Exhibits 2 and 9.

3. How much methane will evaporate per day from a tank 50 ft. in diameter and 25 ft. high insulated by 4 inches of balsa wood when the outside temperature is 70° F.? The K factor for balsa wood (cross grain) is given in Fig. 4. The amount of heat required to evaporate 1 pound of methane is 220 BTU. What is the accuracy of these calculations? List the most important factors which you have neglected.

II. Suggestions for some more advanced engineering problems:

1. The balsa insulation was pre-compressed during installation. The strains were 1/4" in 4 ft. across grain and 3/16" in 16 ft. end grain. Can you conclude anything about coefficients of thermal expansion, moduli of elasticity, or yield strengths from these facts? Can you make your conclusions more specific if you assume that balsa wood behaves like a bundle of tubes?

2. To liquefy LNG by cooling it to its boiling point takes energy, say E watts per kg. What about the reverse process, conversion of this liquid to a gas at 70° F? Does it again require energy? Or can we recover some of the energy used for cooling?

What fraction of E must be spent to gasify or can be recovered when we gasify?

3. All materials have hysteresis (damping) when deformed and also have dimensional changes with temperature. If rubber, for example, is compressed and then frozen, the pressure can be released and the compression will remain. If a simple piece is stretched and then frozen it will remain stretched. Thus two pieces of rubber could be examined by someone in a cold room and found to be rubber of the same size and shape and to have the same modulus of elasticity, but the pieces would not be duplicates. Can this happen with insulating material? With metals? What is the missing parameter? Can it happen at room temperature?

III. Questions related to economics:

1. Can you mention any commodity whose value is as far above its cost as was the value of gas at 6 cents per 1000 cu. ft. in 1950? (Note that gas now being brought to this country will cost 90 cents to $1.20 per 1000 cu. ft.)

2. Can you think of any other commodity for which a surplus is available in one part of the world and a demand exists elsewhere which cannot be met because of transportation costs?

3. If somebody has a good idea which promises 20% yearly profit on invested capital, but requires at least $50 million to start, how can he obtain the required "risk capital"?

4. What percentage of its profit (average over past 5 years) can a large oil company risk in the venture described above if the chances of success are: a) 50:50, b) 10:1, c) 1:10?

5. Is the supply of risk capital in this country affected by a) inheritance taxes, b) depletion allowances, c) capital gains taxes?

6. What salable by-products or services are theoretically (and possibly economically) available when transporting liquefied natural gas?